

INTERPLANETARY SHOCK EFFECTS ON THE NIGHTSIDE AURORAL ZONE, MAGNETOSPHERE AND IONOSPHERE

B.T. Tsurutani and X.-Y. Zhou

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA91109, USA

ABSTRACT

Responses of the nightside magnetosphere and auroral zone to interplanetary shocks are studied using WIND solar wind data and POLAR UV imaging data. It is found that the nightside magnetospheric/ionospheric response depends on the interplanetary magnetic field upstream of the shock. When the IMF B_z is strongly southward upstream (up to 1.5 hr) of the shock, a substorm expansion phase is triggered by the shock. If the IMF B_z is ~ 0 , the interplanetary shock triggers a pseudobreakup. If the B_z is northward, the shock does not trigger nightside auroral activity. Shock compression effects on the magnetotail are discussed, as well as potential substorm triggering mechanisms. A schematic model for tail plasma "loading" and "unloading" is presented. One conclusion of this paper is that it may now be possible to predict what type of auroral activity occurs after interplanetary shock impingement on the magnetosphere/magnetotail. A "dripping, tilting bucket" model is presented to explain the observations. The model incorporates the possibility that the magnetotail has a nonlinear response to unusually strong interplanetary shocks.

INTRODUCTION

Interplanetary shocks have been known to trigger magnetospheric substorms since the 1970's. These earlier results reported that substorm triggerings are associated with shock intensities (Schieldge and

Siscoe, 1970; Kawasaki et al., 1971), and interplanetary magnetic field (IMF) preconditions (Burch, 1972; Kokubun et al., 1977). Kokubun et al. (1977) noted that ~43% of interplanetary shocks triggered substorm expansion phases.

In this paper, WIND interplanetary and POLAR UV imaging data are used to characterize interplanetary shocks and nightside auroras, respectively. A more complete set of observational results can be found in Zhou and Tsurutani (2000). The consequences of shock compression of the magnetotail are discussed in light of previously published substorm triggering models. A schematic model is presented to explain the flow of energy from the interplanetary space to the magnetosphere and to the ionosphere for shock-triggered substorm expansion and pseudobreakup events.

OBSERVATIONS

Interplanetary shocks occurring in 1997 and 1998 are used in this study (see also Zhou and Tsurutani, 2000). The resultant geomagnetic events are classified into three types based on the nightside auroral response. They are: 1) intense nightside auroral brightening/substorm expansion phase onsets; 2) pseudobreakups, and 3) auroral quiescent events. Figure 1 shows three interplanetary shocks observed by WIND in the upstream solar wind in 1997 and 1998. Shown in the Figure are shocks that trigger: a) an intense nightside auroral brightening (substorm?), b) a pseudobreakup event and c) a quiescent event (no enhanced aurora). In each panel from top to bottom are the IMF magnitude, the IMF B_z component, the solar wind plasma temperature, proton density, and velocity, the solar wind ram pressure (defined as $P_{\text{ram}} = \rho V^2$, where ρ is the mass density of protons and V is solar wind speed), and geomagnetic AE indices. Vertical dashed lines indicate the times of shock occurrence.

For the Sep 24, 1998 shock event (panel a), the IMF B_z average over the 1.5 hr preceding the shock (henceforth called the precondition) is -1.8 nT. At the shock, B_z turned northward from ~ -1 to 3 nT. P_{ram} increased from ~ 4 to 16 nPa. The shock triggered a substorm further expansion as shown by the bottom panel, AE increased from ~ 700 to 1500 nT. For the Jan 10, 1997 shock event, the IMF B_z precondition was +0.3 nT. The IMF B_z turned northward from $\sim +1$ to +5 nT and P_{ram} increased from ~ 2 to 5 nPa across the shock. AE increased from ~ 20 to 50 nT. For the June 25, 1998 shock event, the IMF B_z precondition was +10 nT. At the shock, the IMF B_z became enhanced, increasing from ~ 9 to 13 nT. The P_{ram} increased from ~ 4 to 7 nPa. The geomagnetic activity was very low, as shown by $\text{AE} < 80$ nT before 1714 UT.

Figure 2 shows nightside auroral regions of northern hemisphere in the geomagnetic coordinates. Panels 1 to 3 are auroral images for the substorm "further expansion" event, pseudobreakup event and the quiescent event, respectively. Images in panels (a) are those just after shock arrival to the magnetosphere. For the Sep 24, 1998 event (Panel 1), before the shock arrival there was substorm activity at ~ 2100 UT (not shown), which presumably corresponded to the "precursor" southward IMF B_z upstream of the shock. After the shock arrival, there was a substorm auroral further expansion at ~ 2347 UT (panel b). The aurora near ~ 21 LT intensified and expanded poleward to $\sim 73^\circ$ Mlat at ~ 2354 UT (panel e). The corresponding peak AE index was ~ 1500 nT, as shown by Figure 1(a).

An auroral pseudobreakup event is shown in Figure 2, Panel 2. Approximately 12 min after the shock arrival at the magnetosphere (panel c), an auroral spot occurred at midnight. This spot decayed after ~ 3 min and intensified again at ~ 0134 UT as shown by Panels 2(d) and (e). Then it decayed (not shown) (see Arballo et al., 1998 for a more detailed discussion of this "quasiperiodicity"). This auroral spot is considered as a pseudobreakup event based on our studies in Zhou and Tsurutani (2000) and Zhou et al. (2000).

Panel 3 shows a quiet nightside auroral oval. There were no near-midnight auroral brightenings within more than half an hour after the shock arrival. Correspondingly, the AE index was very low (shown in Figure 1(c)). We call this a "quiescent" event.

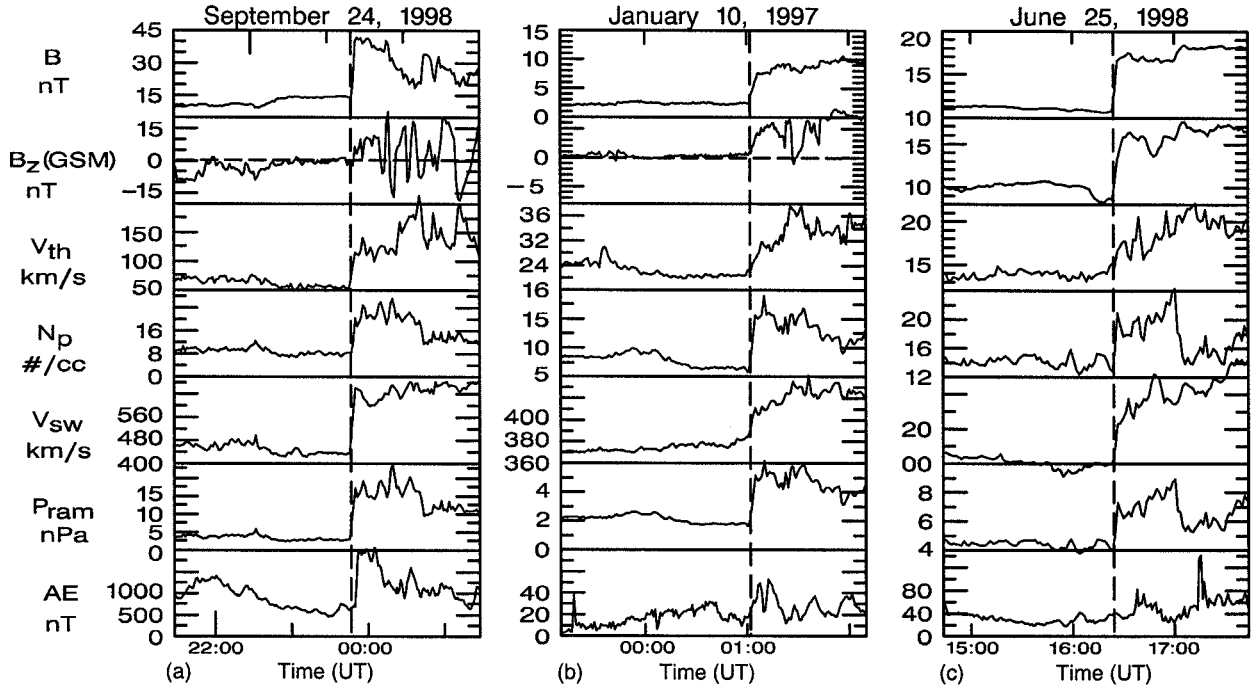


Figure 1. Interplanetary shock events detected by WIND. The WIND magnetic field and plasma data have been "time shifted" to the magnetopause. For the September 24, 1998 shock event (panel a), WIND was in the upstream solar wind at about (184, 13, -9 Re) in GSM coordinates. Panel (b) shows the January 10, 1997 event. WIND was located at (85, -55, -22 Re). Panel (c) shows the June 25, 1998 shock event. WIND was at (69, 66, -1 Re).

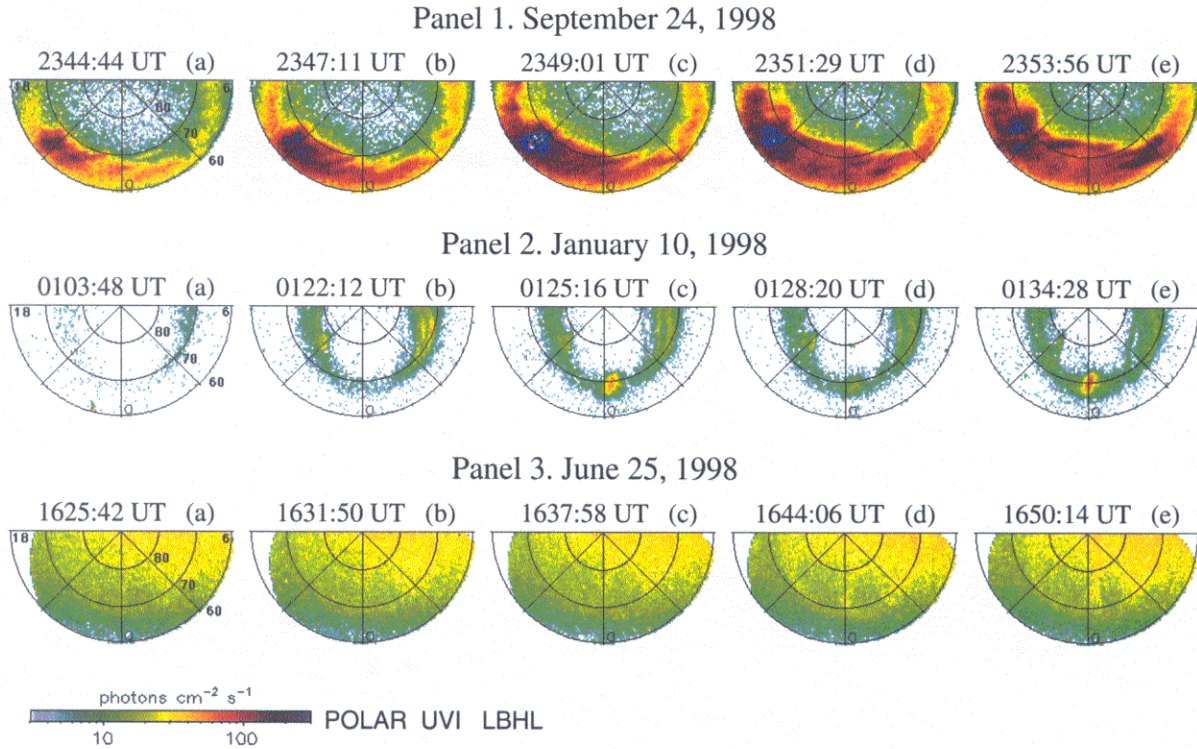


Figure 2. Nightside auroral activity during the September 24, 1998 (Panel 1), January 10, 1997 (Panel 2), and the June 25, 1998 (Panel 3) shock events. For each image, dawn is on the right and midnight at the bottom. The time sequence goes from (a) to (e) for each event. The images are taken from the LBHL filter (~ 170 nm) with a 36.8 sec exposure time.

For all 18 events studied, results similar to the three events of Figure 1 and 2 were found. Our general findings are: 1) with southward IMF B_z preconditions, substorm expansion phases were triggered by interplanetary shocks; 2) with IMF $B_z \sim 0$ preconditions, pseudobreakups occurred; 3) with extreme northward IMF preconditions, there was no midnight auroral activity triggered by interplanetary shocks.

INTERPLANETARY SHOCK EFFECTS ON THE MAGNETOTAIL

Compression Effects of Interplanetary Shocks on the Magnetotail

Below, we discuss the effects of solar wind compression of the near-Earth magnetotail. Pressure balance between the solar wind and the tail geomagnetic field is assumed. The tail lobe geometry is primarily

determined by the component of solar wind ram pressure normal to the tail magnetosphere boundary and secondarily, by solar wind static pressure. The equilibrium expression is:

$$\frac{B_L^2}{8\pi} = (n_p + n_{He})V_{SW}^2 \sin^2 \alpha + nk(T_e + T_p) + \frac{B_{SW}^2}{8\pi} \quad (1)$$

Here B_L is the tail lobe magnetic field strength (we assume that the lobe plasma pressure is negligible), α is the tail flaring angle (the angle between the solar wind flow direction and the tangent to the magnetopause surface), T_e and T_p are the interplanetary electron and proton temperatures, and B_{SW} is the interplanetary field strength. n is the plasma density and k is the Boltzmann constant. The first term on the right-hand side is the component of the solar wind ram pressure perpendicular to the tail magnetopause. The second and third terms are the solar wind plasma thermal pressure and magnetic pressures. In this paper, we have called the sum of the latter two terms the “solar wind static pressure”.

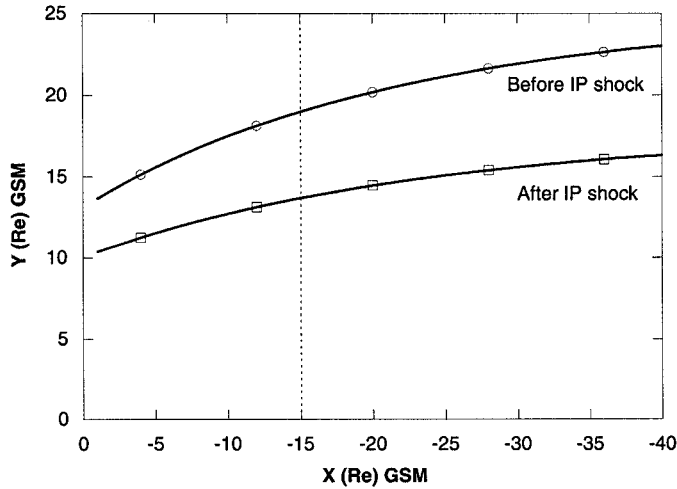


Figure 3. The tail magnetopause position ($X \leq 0$) during the Sep 24, 1998 event. At $X = -15$ Re in the tail, the radius of the magnetopause is decreased from 19 Re to 13.7 Re by the solar wind ram pressure.

Figure 3 shows the magnetopause positions in the X-Y GSM plane before and after the interplanetary shock compression during the Sep 24, 1998 event. The calculation is based on the Petrinec and Russell (1996) model (which only considers the solar wind ram pressure). At $X = -15$ Re (down tail), the magnetopause radius is reduced from 19 to 13.7 Re. By adding the static pressure, we calculate that this radius is reduced

further to 13.3 Re. Assuming that magnetic flux in the tail lobes is conserved (no extra flux is added to or reconnected in the tail), the radius of the tail lobe is reduced from 19 to 13.3 Re (at $X = -15$ Re). The magnetic field in the lobes will thus increase by a factor of ~ 2.1 .

The magnetopause configuration and tail cross-section are sketched in Figure 4 (a) prior to and (b) after shock compression. The stronger the interplanetary shocks are, the stronger the magnetotail compression. As the lobe magnetic field strength is increased, the cross-tail current density will increase accordingly (as shown in Figure 4b). This follows due to the equivalence between the lobe field strength and the currents confining the fields.

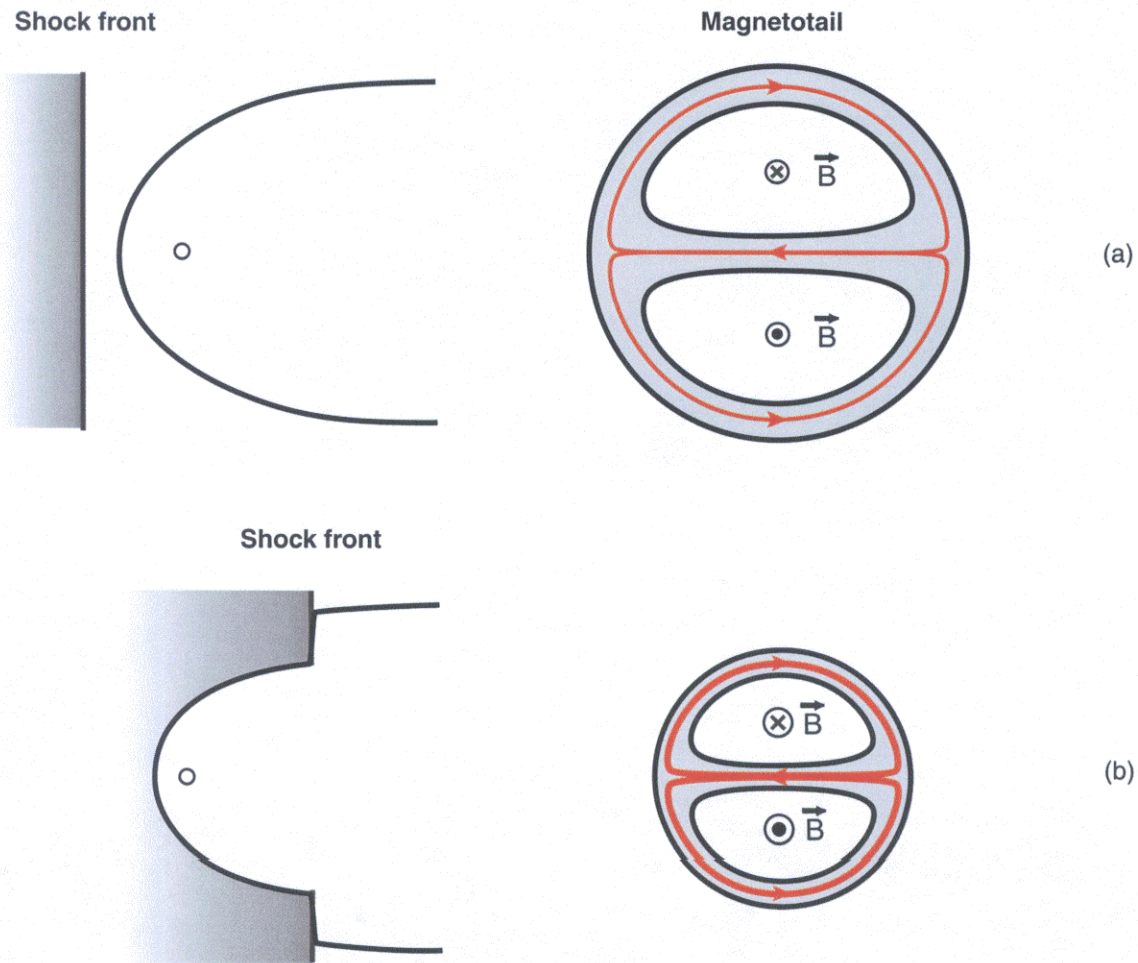


Figure 4. The magnetopause and magnetotail configurations prior to and after interplanetary shock compression.

Current Sheet Disruption

As proposed by Lui et al. (1990), the current sheet disruption can be triggered by the kinetic cross-field streaming instability (KCSI). This instability can set in when the drift speed between electrons and ions

are sufficiently large such that electron Landau damping is overcome by the ion contribution to growth. The cross-tail current will be enhanced by the magnetotail compression. However, calculations (and measurements) are needed to determine whether the onset of the KCSI instability takes place during such compressions or not.

X-Line Formation

When the IMF turns southward, dayside magnetic reconnection is activated. Dayside magnetic flux is transported over the polar caps to the outer portions of the tail lobes. The accumulated magnetic flux in the tail lobes will change the magnetic configuration including thinning of the plasma sheet and earthward motion of current sheet (Coroniti and Kennel, 1972; McPherron, 1991 Figure 59). When interplanetary shocks compress the magnetotail, the lobe magnetic field will increase further, especially the B_x component. The magnetotail is effectively stretched. Coroniti (1985) and Baker and McPherron (1990) postulated that when the vertical component of magnetic field across the plasma sheet becomes sufficiently small, ions in the cross-tail current no longer behave adiabatically, and magnetic reconnection begins in the central plasma sheet. Then the rate of reconnection increases explosively. It has been indicated (de la Baeujardiere et al., 1991 and Blanchard et al, 1997) that substorm expansion phase is associated with increased magnetic reconnection the magnetotail. This scenario can be studied as well using shock events as time markers.

A DRIPPING, TILTING BUCKET MODEL

To illustrate the findings in this paper and our conceptual ideas, a schematic is provided in Figure 5. On the left hand side of the figure, solar wind energy is put into the plasma sheet by dayside magnetic reconnection (the small pail putting water into the bucket). The greatest rate of energy input occurs when

the IMF has a large southward component (top left panel), less so when $B_z \approx 0$ (middle left panel), and the least, when the IMF has a completely northward component (bottom left panel).

The energy flows out of the bucket in two ways, through the spigot and through holes in the bucket. The energy flow through the spigot represents energy into the magnetospheric/ionospheric system: storms, substorms and pseudobreakups. The "leakage" represents energy dissipation down tail or into the magnetosheath.

This "dripping" or leakage is implied from the limited ~ 1.5 hr "priming" found in this study and many other previous works (such as Arnoldy (1971), Tsurutani and Meng (1972) and Meng et al. (1973) and many others). If the energy was stored in the plasma sheet for much longer time intervals, the relationship found here and the previously cited works showing high IMF B_s -AE correlations would not be present. What exactly are these loss processes? At this time we don't exactly know. But several possibilities are internal dissipation and down tail energy flow. Ho and Tsurutani (1997) have argued that deep tail magnetic reconnection is not related to substorm activity, so this "magnetotail sloughing" may be one possible dissipation mechanism.

On the right hand side of Figure 5 are the interplanetary shock effects. The shock "tilts" the bucket. The stronger the shock, the greater the tilting. In the top right panel, the shock (bucket tilting) leads to substorm "intensification". At this time, more energy is pouring out from the spigot (there is more energy going into the ionosphere than the solar wind is transferring to the plasma sheet).

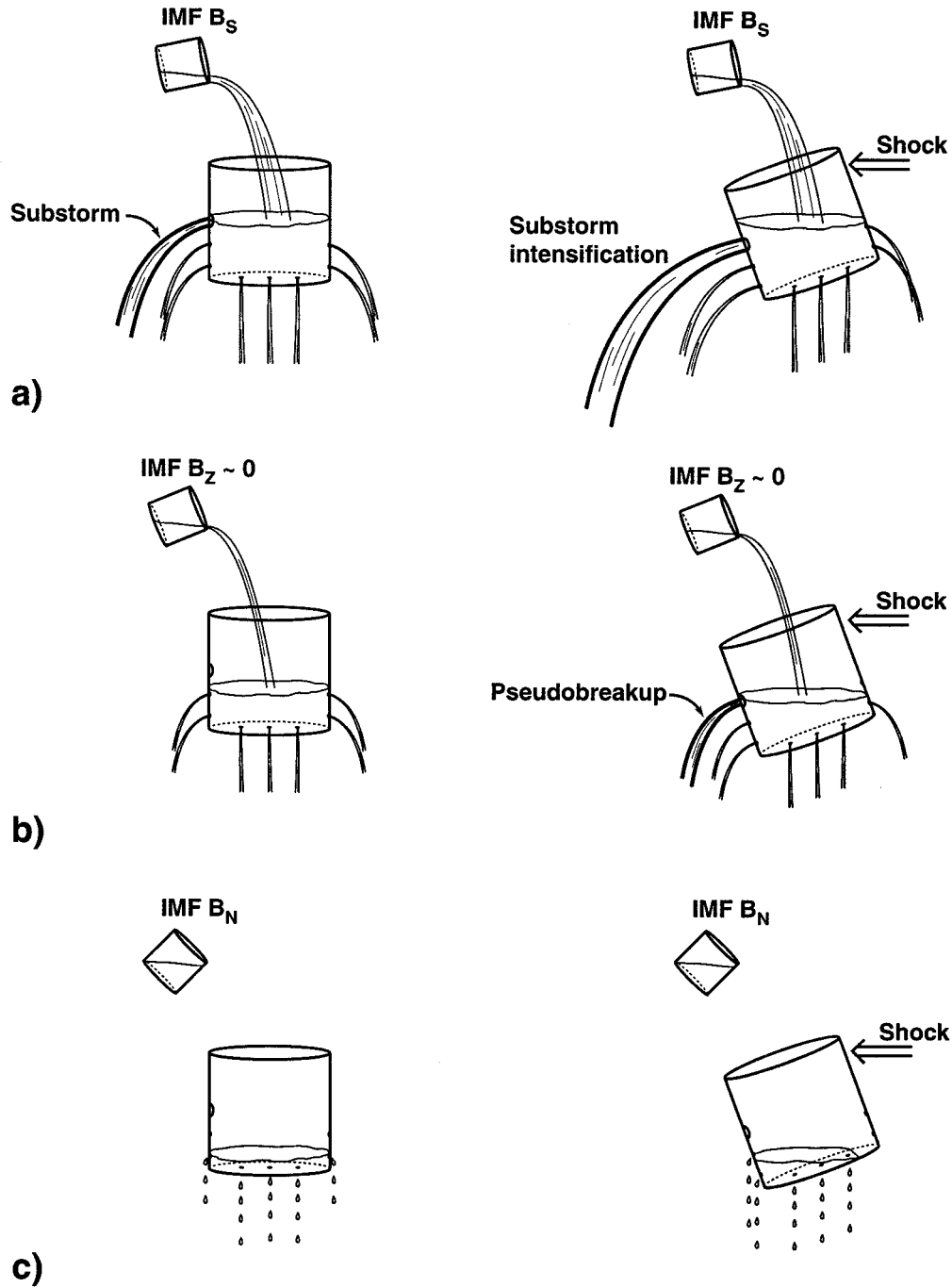


Figure 5. A schematic of the Dripping, Tilting Bucket model.

For cases where the plasma sheet energy storage level is relatively low (middle right panel), a moderate shock leads only to a pseudobreakup (small substorm). A stronger shock corresponds to greater bucket tilting, and a substorm.

For very low energy storage (bottom right panel), a moderate shock leads to no energy output. However, for a very strong shock, a pseudobreakup or even a substorm are possible outcomes.

In the above model, the IMF B_z (dayside magnetic reconnection) plays the role in the filling of the bucket. The shock compression and cross-tail current sheet microinstabilities are represented by the tilting of the bucket. The “dripping, tilting bucket” model has been constructed to explain the shock/magnetosphere/ionosphere relationships found in this paper.

FINAL COMMENTS

In this paper and in Zhou and Tsurutani (2000), we discuss plasma loading into the tail by "precursor" IMF B_s fields. This plasma is "loaded" into the tail and then "unloaded" into the magnetosphere triggered by the interplanetary shock compression effects. However, of the 18 shock events studied, there was one "anomalous" event, that of Sep 24, 1998. For this event, Zhou and Tsurutani (2000) found that there was anomalously high energy (AE) output for the IMF B_s "precursor" input. We have shown in this paper that the ram pressure increase across this shock was anomalously high (a factor of 4 increase), that highest of the 18 events studied. Schieldge and Siscoe (1970), Kawasaki et al. (1971) and Kokubun et al. (1977) have also previously noted a geomagnetic activity dependence on shock intensity. Thus it is possible that for very strong shocks, the magnetotail responds in a nonlinear fashion. As one possible scenario, additional energy may be injected into the magnetosphere due to enhanced tail magnetic reconnection (Figure 5a indicated such a potential scenario). In the near future, we will examine strong shock (Mach 3 to 4) versus weak shock effects on the magnetosphere.

ACKNOWLEDGMENTS

Portions of this paper represent work done at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, under contract with the National Aeronautics and Space Administration. T. Araki provided the ground based AL and AE indices, magnetometer data and K. Ogilvie and R.P. Lepping the WIND SWE and MFI data. J.K. Arballo helped in the data processing and software support. X.-Y. Zhou would like to thank the National Research Council for the award of a Resident Associateship at the Jet Propulsion Laboratory.

REFERENCES

- Arnoldy, R.L., Signature in the interplanetary medium for substorms, *J. Geophys. Res.*, 76, 5189 (1971).
- Baker, D.N., and R.L. McPherron, Extreme energy particle decreases near geostationary orbit: a manifestation of current diversion with the inner plasma sheet, *J. Geophys. Res.*, 95, 6591 (1990).
- Blanchard, G.T., L.R. Lyons, and O. de la Beaujardiere, Magnetotail reconnection rate during magnetospheric substorms, *J. Geophys. Res.*, 102, 24303 (1997).
- Borovsky, J.E., M.F. Thomsen, R.C. Elphic, The driving of the plasma sheet by the solar wind, *J. Geophys. Res.*, 103, 17617 (1998).
- Burch, J.L., Preconditions for the triggering of polar magnetic substorms by storm sudden commencements, *J. Geophys. Res.*, 77, 5629 (1972).
- Chang, C.L., H.K. Wong, and C.S. Wu, Electromagnetic instabilities attributed to a cross-field ion drift, *Phys. Rev. Lett.*, 65, 1104 (1990).
- Coroniti, F.V., and C.F. Kennel, Changes in the magnetospheric configuration during the substorm growth phase, *J. Geophys. Res.*, 77, 3361 (1972).
- Coroniti, F.V., Explosive tail reconnection: the growth and expansion phases of magnetospheric substorms, *J. Geophys. Res.*, 90, 7427 (1985).
- de la Beaujardiere, O., L.R. Lyons, and E. Friis-Christensen, Sondrestrom radar measurements of the reconnection electric field, *J. Geophys. Res.*, 96, 13907 (1991).

- Ho, C. M., and B.T. Tsurutani, Distant tail behavior during high speed solar wind streams and magnetic storms, *J. Geophys. Res.*, 102, 14165 (1997).
- Kawasaki, K., S.-I. Akasofu, F. Yasuhara, and C.-I. Meng, Storm sudden commencements and polar magnetic substorms, *J. Geophys. Res.*, 76, 6781 (1971).
- Kokubun, S., R.L. McPherron, and C.T. Russell, Triggering of substorms by solar wind discontinuities, *J. Geophys. Res.*, 82, 74 (1977).
- Lennartsson, W., and E.G. Shelley, Survey of 0.1- to 16-keV/e plasma sheet ion composition, *J. Geophys. Res.*, 91, 3061 (1986).
- Lui, A.T.Y., A. Mankofsky, C.-I. Chang, K. Papadopoulos, and C.S. Wu, A current disruption mechanism in the neutral sheet: a possible trigger for substorm expansions, *Geophys. Res. Lett.*, 17, 745 (1990).
- McPherron, R.L., Physical processes producing magnetospheric substorms and magnetic storms, in *Geomagnetism*, vol., edited by J.A. Jacobs, pp. 593, Academic, San Diego, Calif., (1991).
- Meng, C.-I., B. Tsurutani, K. Kawasaki, and S.-I. Akasofu, Cross-correlation analysis of the AE index and the interplanetary magnetic field Bz component, *J. Geophys. Res.*, 78, 617 (1973).
- Petrinec, S.M., and C.T. Russell, Near-Earth magnetotail shape and size as determined from the magnetopause flaring angle, *J. Geophys. Res.*, 101, 137 (1996).
- Schieldge, J.P., and G.L. Siscoe, A correlation of the occurrence of simultaneous sudden magnetospheric compressions and geomagnetic onsets with selected geophysical indices, *J. Atmos. Terr. Phys.*, 32, 1819 (1970).
- Spann, J., and G. Germany, Global auroral response to a solar wind pressure pulse, *Advances in Space Research*, 25, 1377 (2000).
- Tsurutani, B.T., and C.-I. Meng, Interplanetary magnetic-field variations and substorm activity, *J. Geophys. Res.*, 77, 2964 (1972).
- Zhou, X.-Y., and B.T. Tsurutani, Rapid intensification and propagation of the dayside aurora: Large scale interplanetary pressure pulses (fast shocks), *Geophys. Res. Lett.*, 26, 1097 (1999).

Zhou, X.-Y., and B.T. Tsurutani, Interplanetary shock triggering of geomagnetic activity: Substorms, pseudobreakups and quiescent events, submitted to *J. Geophys. Res.*, (2000).

Zhou, X.-Y., B.T. Tsurutani, W.D. Gonzalez, and A.J. Lazarus, The solar wind depletion event of 26 April 1999: Triggering of a midnight auroral event, *Geophys. Res. Lett.*, in press, (2000).